Fermilab ILC R&D Meeting, May 4, 2005

Top/QCD Physics at the ILC

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Linear Collider Parameters

Baseline Machine

- $(\sqrt{s})_{max}$= 500 GeV but can operate at at any $\sqrt{s}$ in the range 200-500 GeV
- 500 fb^{-1} in first 4 years of running

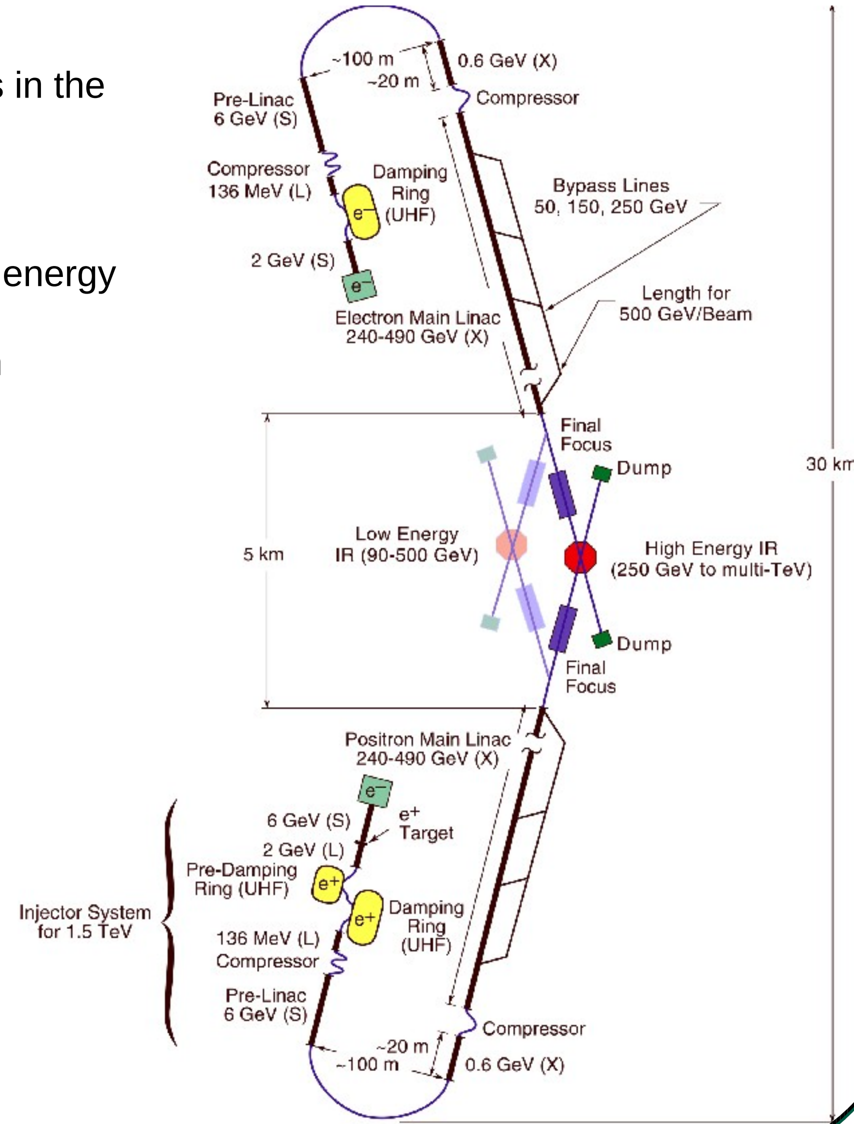
- Possibility of energy scans at any $\sqrt{s}$ in whole energy range
- Possibility to go down to Z peak for calibration
- Beam energy precision < 0.1%
- $P(e^-) \geq 80\%$ in whole energy range
- 2 interaction regions

Upgrade

- $(\sqrt{s})_{max} \sim$ 1 TeV
- 1000 fb^{-1} in ~3-4 years

Options

- Additional 500 fb^{-1} at $\sqrt{s}$ = 500 GeV in 2 years
- $P(e^+) \geq 50\%$ in whole energy range
- Low energy running ($\sqrt{s} = m_Z$ and $2m_W$) with $L \sim 10^{33}$ $cm^{-2}s^{-1}$
- e^-e^- collisions
- $e^-\gamma$ and $\gamma\gamma$ collisions

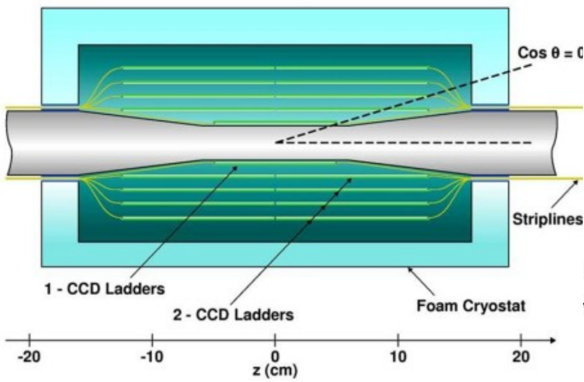


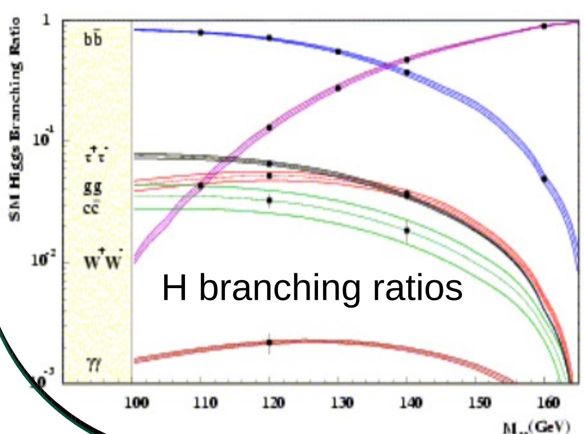
The Generic Detector

- High resolution detector, based on the experience from LEP/SLD and R&D for the LHC.
- Detector design largely driven by performance optimization for Higgs physics.

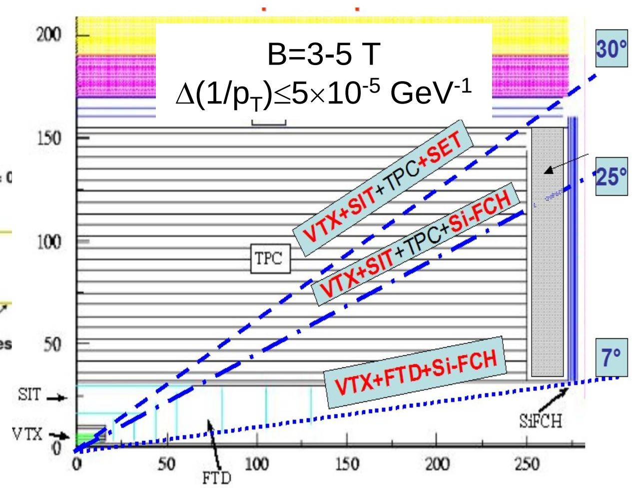
Precision Vertexing

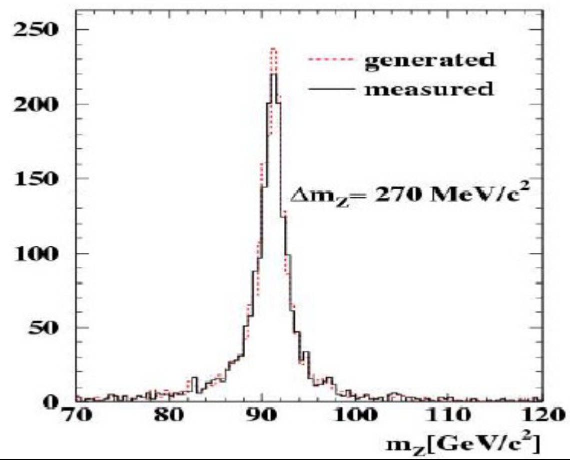
Pixel detector (~3 μm point resolution)
Material<0.1% X_0
R(1^{st} layer) ~1.5 cm



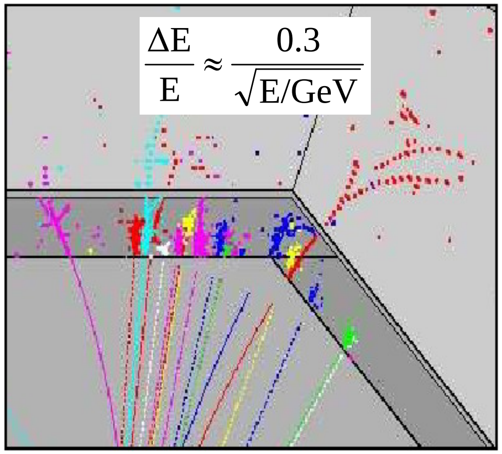


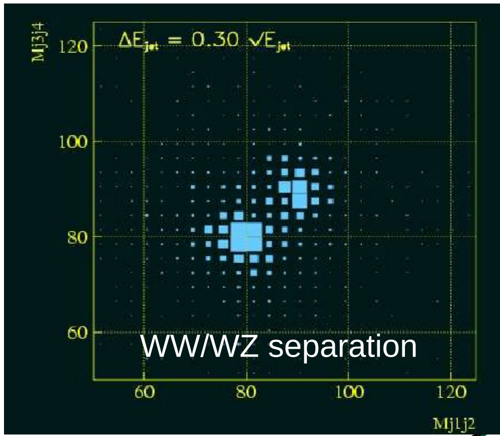
Precision Global Tracking





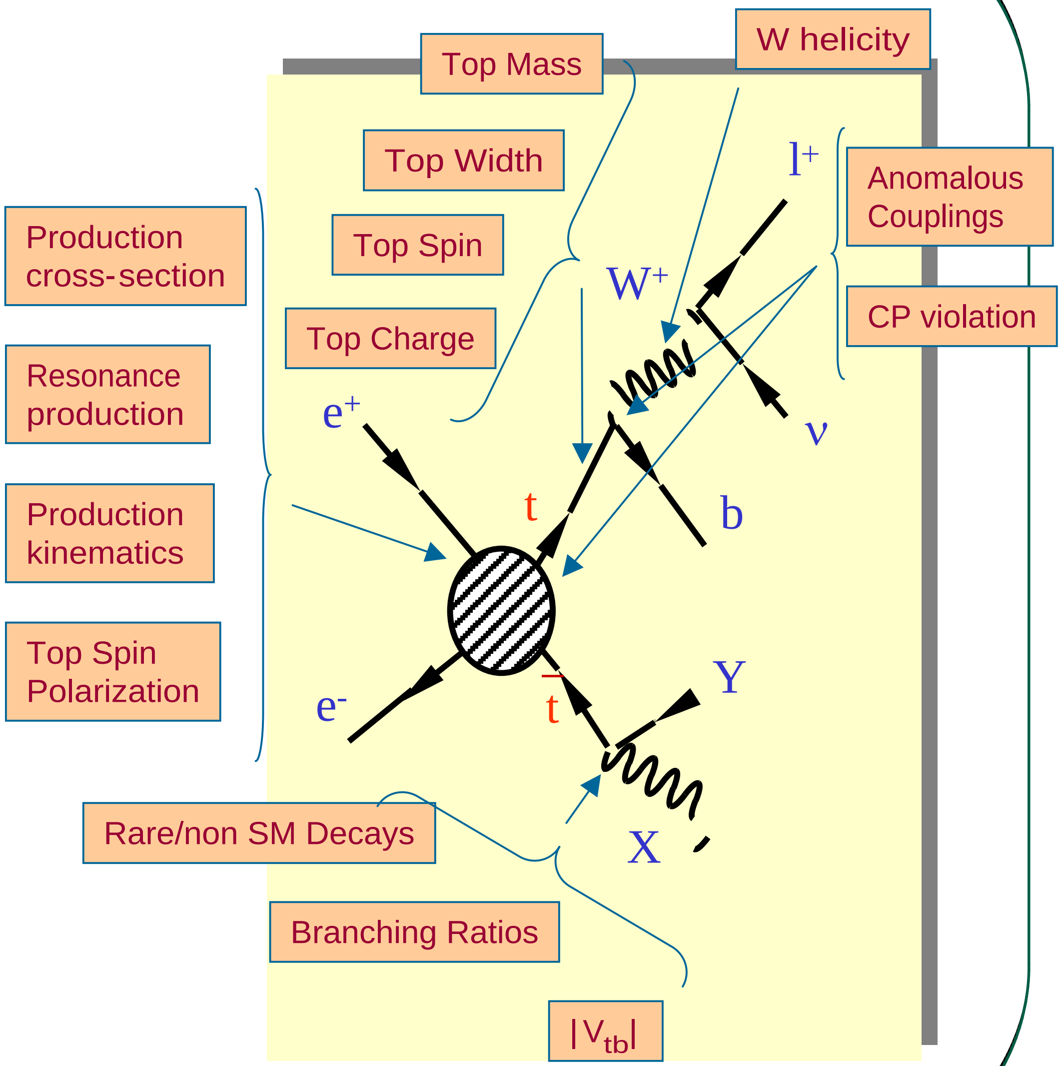
Optimized Calorimetry for Energy Flow





Outlining the Top Quark Profile

- One of the most urgent problems in HEP is to identify the mechanism of EWSB and mass generation, in which the top quark may play a special role.
- The Tevatron/LHC will provide first incisive tests of SM top physics. The LHC has a large potential for discovery of New Physics effects: e.g. heavy tt resonances, FCNC decays, etc…
- High precision measurements in the top sector will be needed to provide hints on the correct underlying theory.

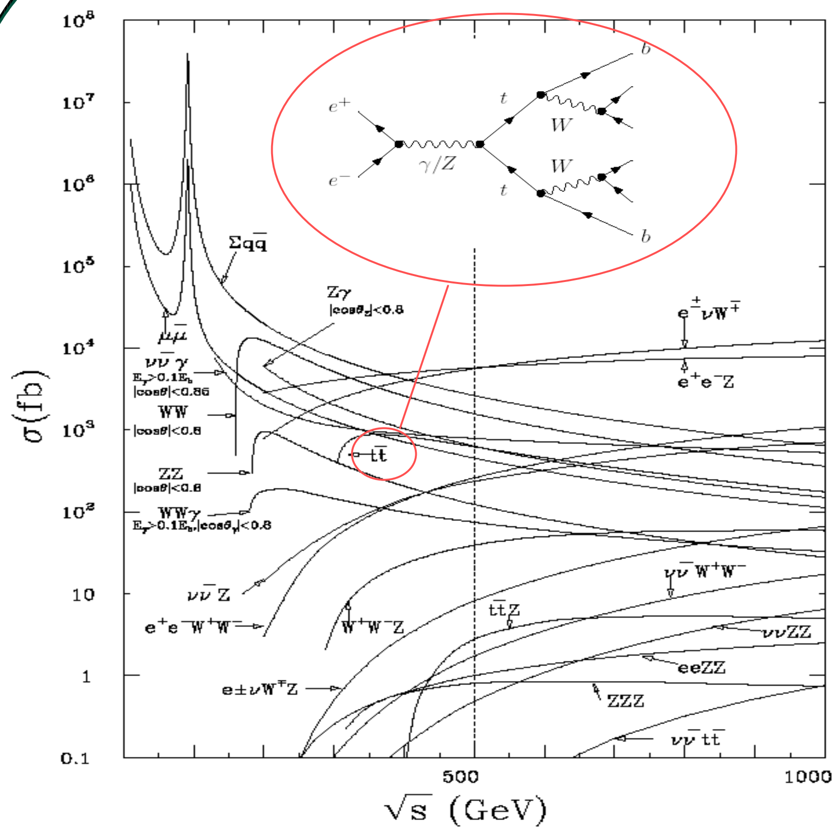


Experimentation at an e^+e^- collider:

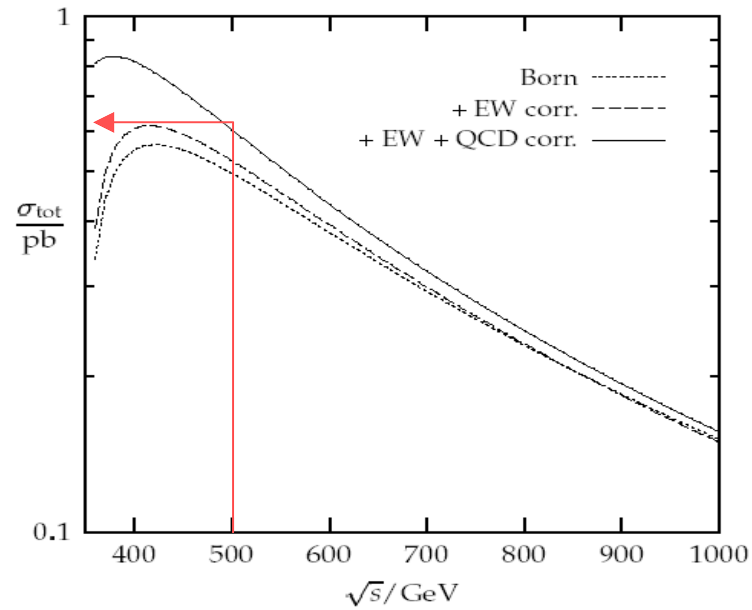
- "clean environment"
  - well defined initial state
  - relatively simple event topologies
  - precise theoretical calculations
- "democracy of cross sections"

  $\Rightarrow$ low backgrounds
- excellent experimental accuracy (high precision detectors, full event reconstruction,…)

Top Production in e^+e^- Collisions



- Top pair production via γ/Z exchange dominates



σ_{tt}~0.6 pb at $\sqrt{s}$=500 GeV

$\Rightarrow$ ~200k events/year (L=2x10^{34}cm^{-2}s^{-1})

- The anticipated experimental accuracy must be matched with precise theoretical predictions

Available:
- Total cross section
  - tt, threshold : NNLL QCD, N(LL) EW
  - continuum: $O(\alpha_s^2)$, $O(\alpha_{EW})$, 2-loop Sudakovs
  - ttH : $O(\alpha_s)$, $O(\alpha_{EW})$, tt threshold effects

Event generators
- $e^+e^- \rightarrow (tt) \rightarrow WbWb$: $O(\alpha_s)$

Will be needed: $e^+e^- \rightarrow 6f$ (lusifer) and $e^+e^- \rightarrow 8f$ to $O(\alpha_s)$
consistent treatment of unstable particles, non-factorizable corrections,…

Top Pair Production at Threshold

- Large Γ_t(~1.4 GeV):
  - $1/\Gamma_t$ >> revolution time of top quark so toponium bound states cannot form
  - Provides IR cutoff, so can use non-relativistic pQCD to compute σ_{tt} near threshold.

    QCD potential essentially Coulombic:

$$V(r) \sim -C_F \frac{\alpha_s(1/r)}{r}$$

- Remants of toponium S-wave resonances induce a fast rise of σ_{tt} near threshold.

  Basic parameters: σ_{tt} (m_t, α_s, Γ_t)
- Convergence of calculation is sensitive to m_t definition used: pole mass is not IR-safe

  $\Rightarrow \sigma_{tt}^{peak}$ not stable vs $\sqrt{s}$

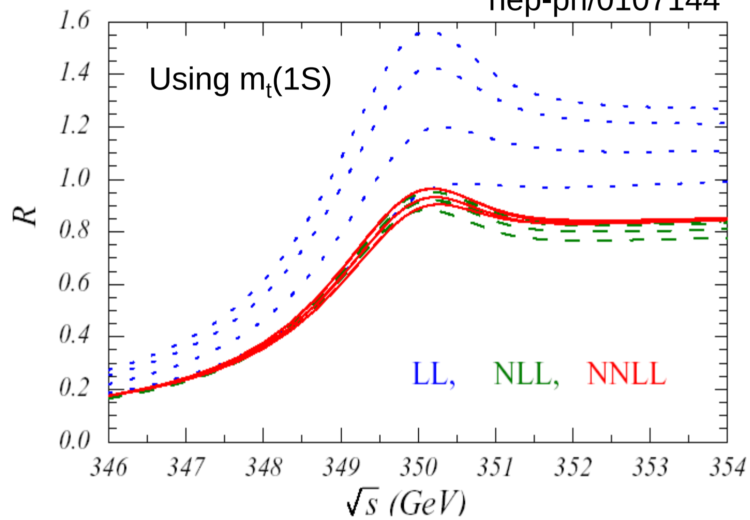
  Solution is to use threshold masses:
  e.g. 1S mass (1/2 the mass of the lowest tt bound state in the limit $\Gamma_t \rightarrow 0$).

  High accuracy in absolute normalization requires velocity resummation (NNLL):

$$(\Delta\sigma_{tt})_{QCD} \leq 3\%$$

- Important to take into account previously neglected %-level effects: non-factorizable corrections, EW box- and triangle-diagrams, W width, interfering backgrounds…

hep-ph/0107144



- Additional observables with different degree of sensitivity to m_t, α_s, Γ_t can also be computed/measured:

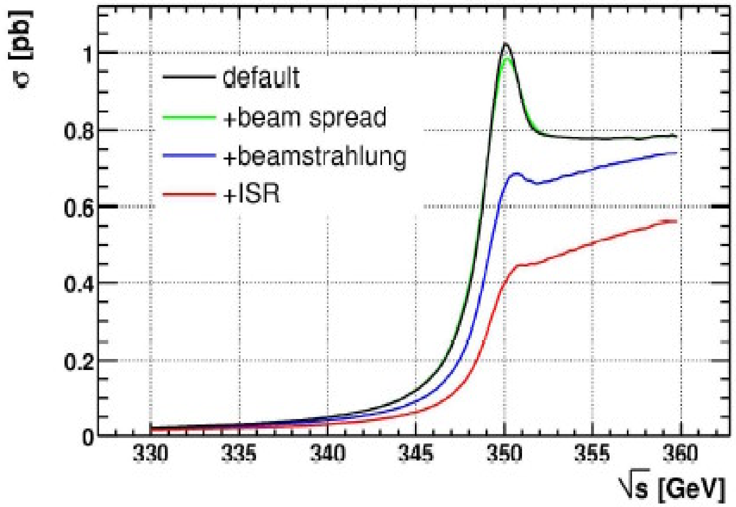
Mainly sensitive to α_s and Γ_t

p_t
A_{FB}

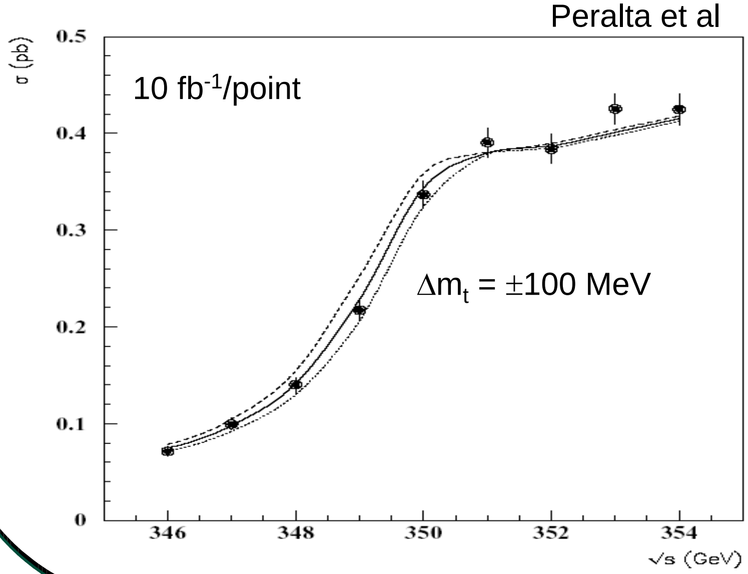
p_t^{peak} rather insensitive to ISR effects due to interference between S- and P-wave states.

- Simultaneous determination of parameters possible when using all threshold observables.

Top Pair Production at Threshold (cont'd)



Peralta et al



- Lineshape significantly distorted due to;
  - Beam energy spread: ~0.1%
  - Beamstrahlung: coherent radiation due to beam-beam interactions. Must be measured precisely (acollinearity in Bhabha events).
  - Bremsstrahlung (ISR): can be calculated accurately

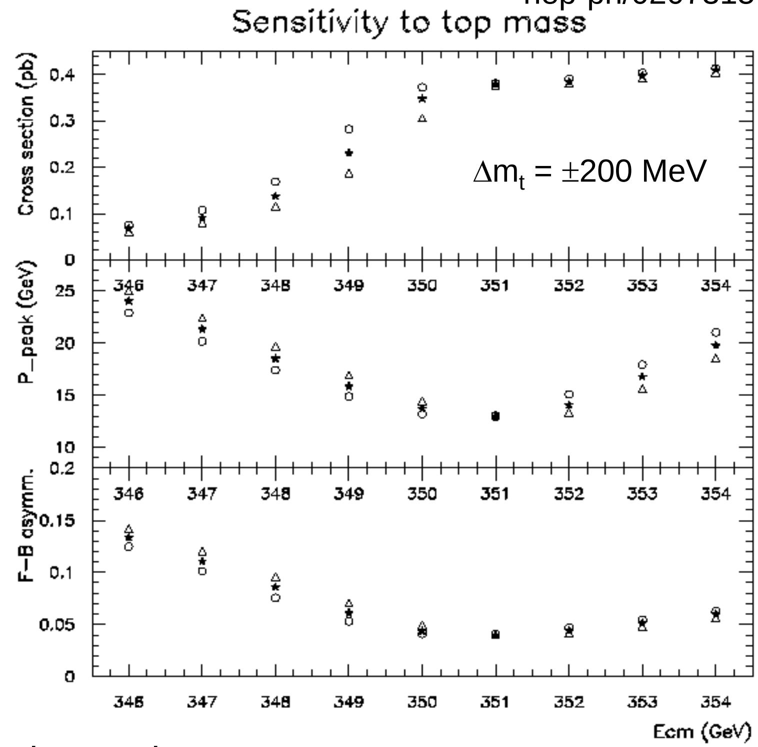
- Perform scan in √s around the threshold region and compare measurement of various observables to theoretical predictions as a function of model parameters.

For instance (hep-ph/0207315):

- 300 fb^{-1} uniformly distributed among 10 points, one of them well below the threshold to measure the background.
- Consider lepton+jets and alljets final states: ε_{tt}~40%, σ_{bckg}~0.0085 pb

Top Quark Mass

hep-ph/0207315



<u>At threshold</u>

- Simultaneous determination of m_t and α_s from fit to threshold observables. Assume 3% theoretical error on σ_{tt}.

  σ_{tt}, p_t^{peak} and A_{FB}:

  $\Delta m_t(1S)=16$ MeV, $\Delta\alpha_s=0.0012$, $\rho=0.33$
- Correlation between m_t and α_s reduced by using 1S mass as compared to the pole mass.
- Ongoing work to evaluate systematic due to luminosity spectrum measurement ($\Delta m_t \leq 50$ MeV).
- Determined from a color singlet (tt system).

  Conversion to $m_t(\overline{MS})$ known accurately

  Δm_t(theo)~100 MeV

Alljets channel

Force event to 6 jets

Minimum set of cuts:

$$|M_{123} - M_{456}| < 40\,GeV$$

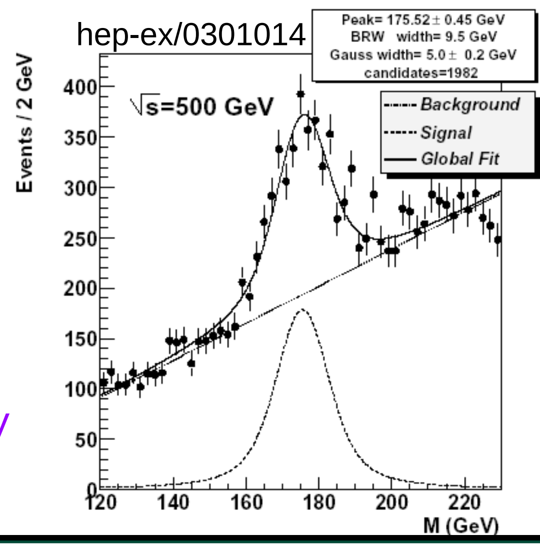
$$|\vec{P}_{123} - \vec{P}_{456}| < 20\,GeV$$

No kinematic fitting or b-tagging.

Δm_t(stat)~100 MeV

L=300 fb^{-1}

hep-ex/0301014



<u>In the continuum</u>

- Direct reconstruction can yield competitive statistical uncertainties. Better understanding of experimental systematic uncertainties needed.
- What's being determined is the pole mass(?).

  Conversion to $m_t(\overline{MS})$ suffers from large renormalon ambiguity:

  Naively: Δm_t(theo)~500 MeV

Impact of a Precise m_t Measurement

- Important ingredient for EW precision analyses at the quantum level. ILC precision on m_t will be needed to match future experimental/theoretical accuracy on M_W and $\sin^2\theta_{eff}$:

Experimental	Today	Tevatron/LHC	ILC	GigaZ
$\delta \sin^2\theta_{\rm eff}(\times 10^5)$	16	14–20	–	1.3
δM_W [MeV]	34	15	10	7

Intrinsic theoretical: $\delta M_W = 4$ MeV, $\delta\sin^2\theta_{eff} = 4.9\times10^{-5}$

Parametric theoretical:

$\delta m_t = 4.3$ GeV $\Rightarrow \delta M_W = 26$ MeV, $\delta\sin^2\theta_{eff} = 14\times10^{-5}$

LHC: $= 1.5$ GeV $\Rightarrow \delta M_W = 9$ MeV, $\delta\sin^2\theta_{eff} = 4.5\times10^{-5}$

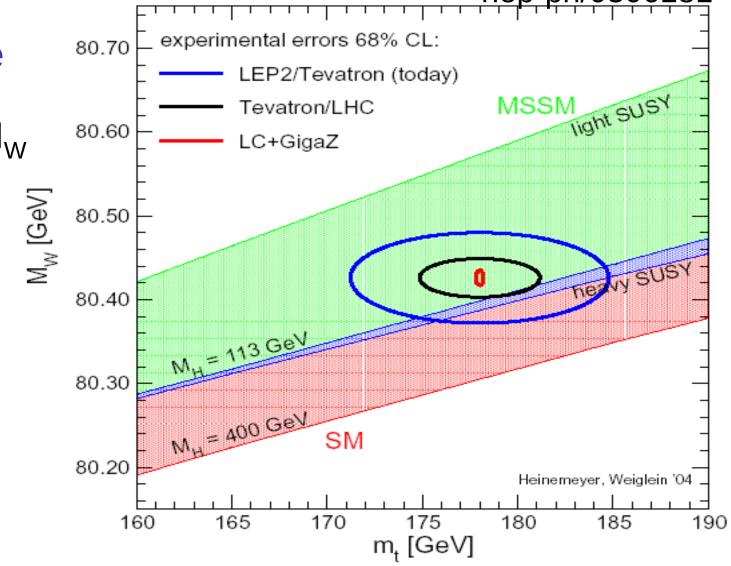
ILC: $= 0.1$ GeV $\Rightarrow \delta M_W = 1$ MeV, $\delta\sin^2\theta_{eff} = 0.3\times10^{-5}$

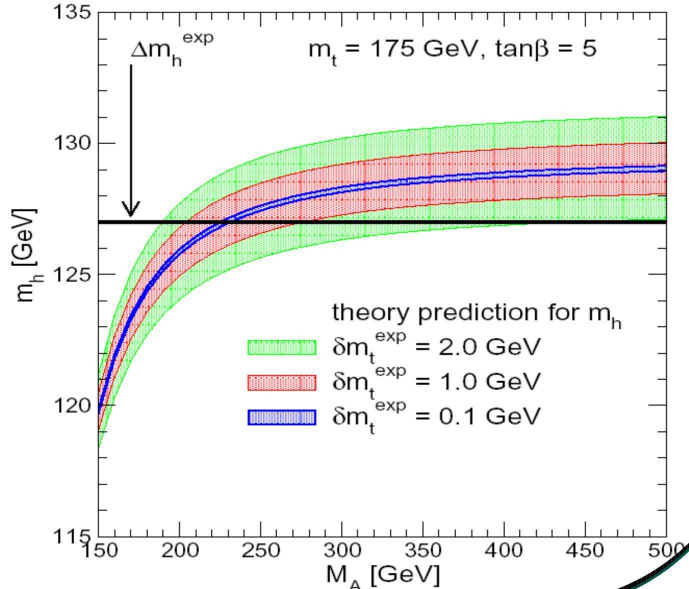
- M_H depends sensitively on m_t in all models where M_H can be predicted (e.g. MSSM).

  Need LC precision on m_t in order to exploit LHC (and LC) precision on Higgs sector measurements.

- Other examples:
  - RGE running to higher scales
  - …

hep-ph/0306181

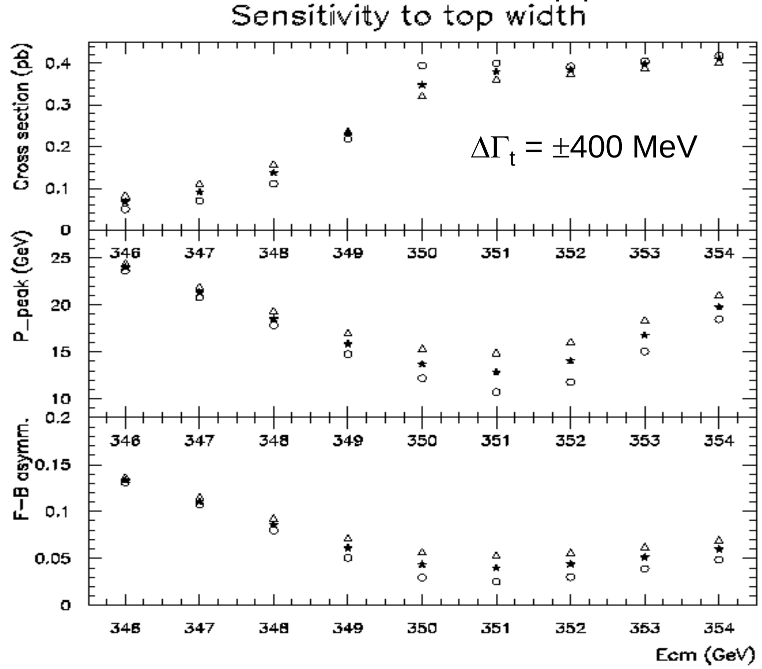




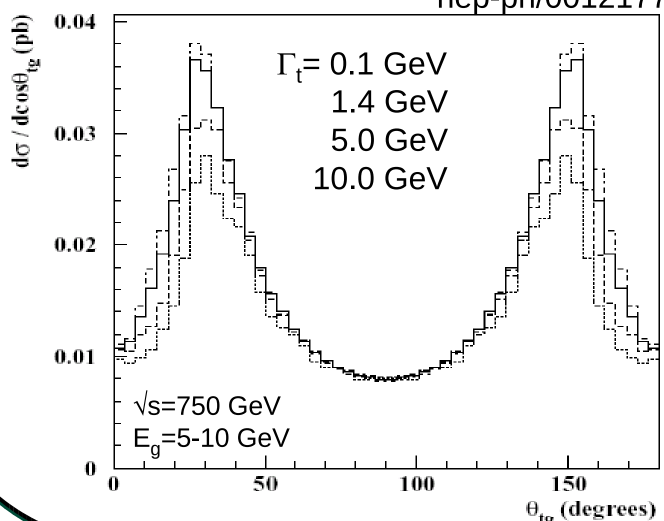
Top Quark Width

- In general, there is no easy way to measure the total top quark width in a model independent way.
  Single top cross-section gives $\Gamma(t \rightarrow Wb)$.
- Threshold observables are sensitive to Γ_t:
  - affects peak structure of 1S resonance
  - $p_t^{peak} \uparrow$ as $\Gamma_t \uparrow$ since the top quark decays at shorter distance where the tt potential is deeper
  - controls overlap between 1S and 1P states: A_{FB}
- Simultaneous determination of m_t, α_s and Γ_t from fit to threshold observables. Assume 3% theoretical error on σ_{tt} and 9+1 point scan with 30 fb^{-1}/point:
  $\Delta m_t(1S)$=19 MeV, $\Delta\alpha_s$=0.0012, $\Delta\Gamma_t$=32 MeV ,ρ_{ij}<0.5

hep-ph/0207315



hep-ph/0012177



- Large Γ_t leads to interesting effects involving the interplay between the strong and weak interactions: soft gluon ($E_g \sim \Gamma_t$) radiation pattern can be affected by Γ_t.
  - At high energy: production-decay interference dominates
  - Near threshold: decay-decay interference dominates
- No experimental study available.

Top Couplings to Gauge Bosons: γ and Z

- Many models of EWSB predict modifications to the couplings between the top quark and electroweak gauge bosons.
- General t-t-γ and t-t-Z vertices:

$$\mathcal{M}^{\mu(\gamma,Z)} = e\gamma^{\mu}\left[Q_V^{\gamma,Z}F_{1V}^{\gamma,Z} + Q_A^{\gamma,Z}F_{1A}^{\gamma,Z}\gamma^5\right] + \frac{ie}{2m_t}\sigma^{\mu\nu}k_{\nu}\left[Q_V^{\gamma,Z}F_{2V}^{\gamma,Z} + Q_A^{\gamma,Z}F_{2A}^{\gamma,Z}\gamma^5\right]$$

Within the SM: $F_{1V}^{\gamma} = F_{1V}^{Z} = F_{1A}^{Z} = 1$ with the rest equal to 0.

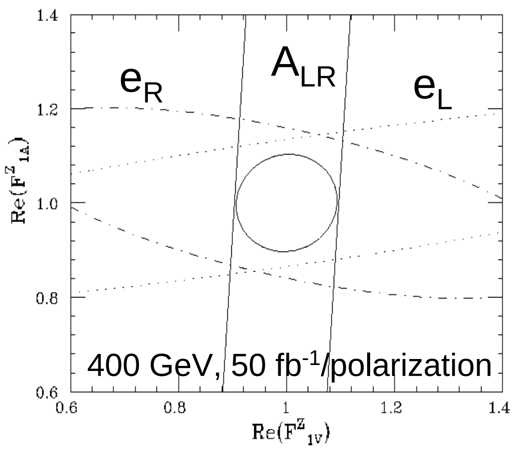
CP-conserving CP-violating

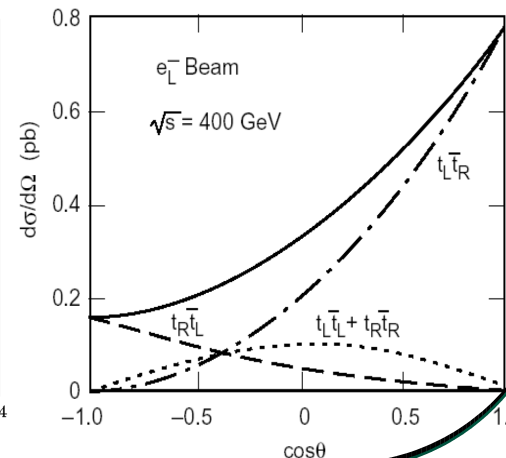
Strong EWSB models (e.g. technicolor): F_{2V}~5-10%
SUSY/MHDM models: F_{2A}~0.1-1%

Tesla TDR

Form factor	SM value	$\sqrt{s} = 500\,\mathrm{GeV}$	
L=300 fb^{-1}		$p = 0$	$p = -0.8$
F_{1V}^{Z}	1		0.019
F_{1A}^{Z}	1		0.016
$F_{2V}^{\gamma,Z} = (g-2)^{\gamma,Z}{}_t$	0	0.015	0.011
$\mathrm{Re}\, F_{2A}^{\gamma}$	0	0.035	0.007
$\mathrm{Re}\, d_t^{\gamma}$ $[10^{-19}$ e cm$]$	0	20	4
$\mathrm{Re}\, F_{2A}^{Z}$	0	0.012	0.008
$\mathrm{Re}\, d_t^{Z}$ $[10^{-19}$ e cm$]$	0	7	5
$\mathrm{Im}\, F_{2A}^{\gamma}$	0	0.010	0.008
$\mathrm{Im}\, F_{2A}^{Z}$	0	0.055	0.010

- Polarization is an important tool to disentangle among different couplings:
  - High sensitivity both at threshold (highly polarized top quarks) and continuum
  - Inclusive polarization observables: $\sigma(e^-_L e^+ \to tt)$, $\sigma(e^-_R e^+ \to tt)$, A_{LR}
  - Angular distributions of final state products





Top Couplings to Gauge Bosons: W

- General t-W-b vertex:

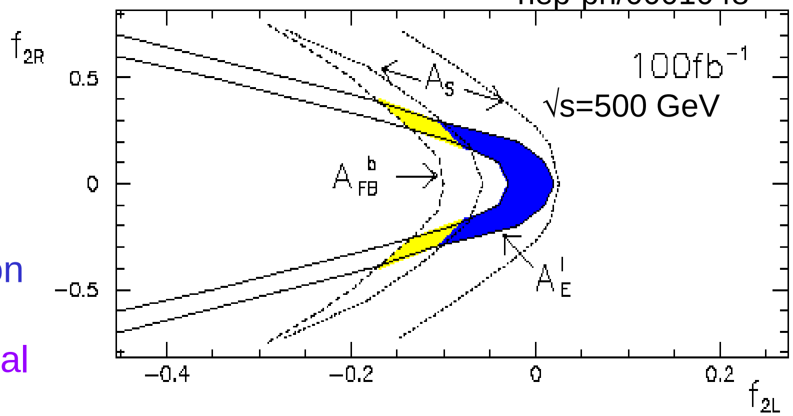
$$\Gamma^{\mu}_{tbW} = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\,\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} \left[f_2^L P_L + f_2^R P_R \right] \right\}$$

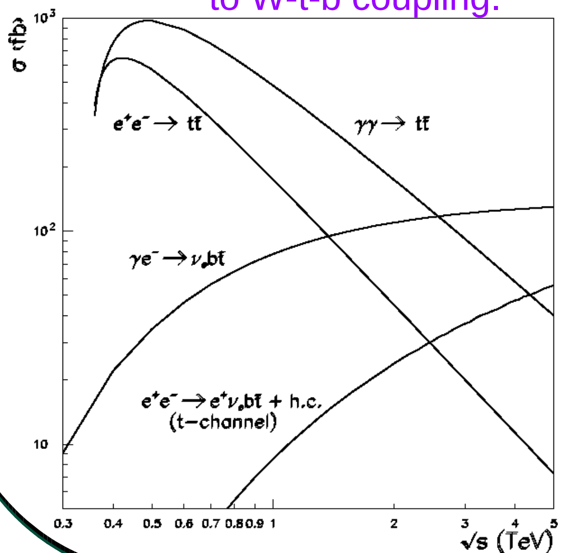
Within the SM: $f_1^L = \overline{f}_1^L = 1$ with the rest equal to 0.

If $f_1^{L,R} - \overline{f}_1^{L,R} \neq 0$ or $f_2^{L,R} - \overline{f}_2^{R,L} \neq 0 \Rightarrow$ CP-violation

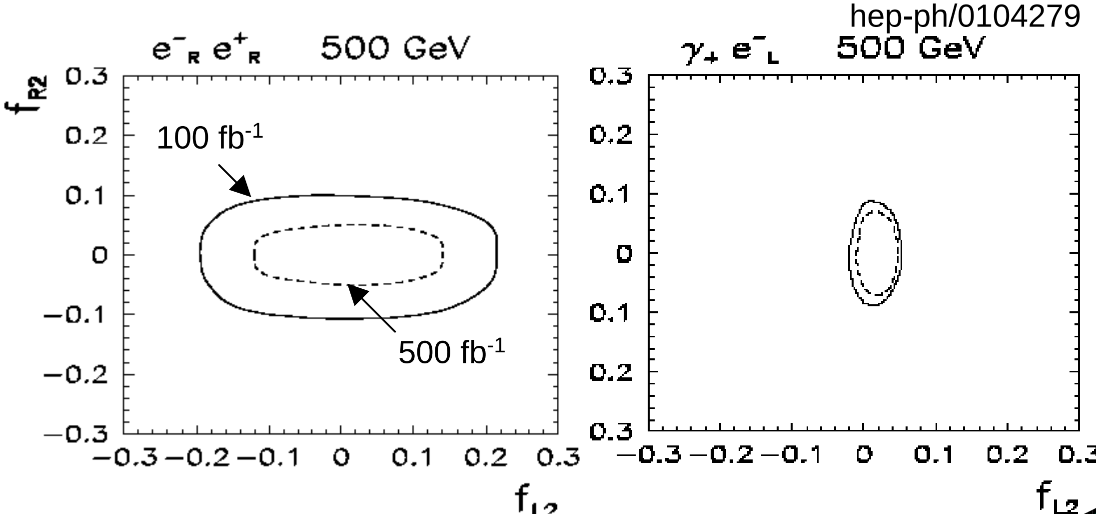
- Tevatron/LHC will measure f_1^R with % accuracy.
- f_2 couplings can be probed in:
  - Top quark production: total rate insensitive. Sensitivity via C and P symmetries, W boson polarization, spin correlations,…
  - Single top quark production: rate proportional to W-t-b coupling.

hep-ph/0001048





hep-ph/0104279



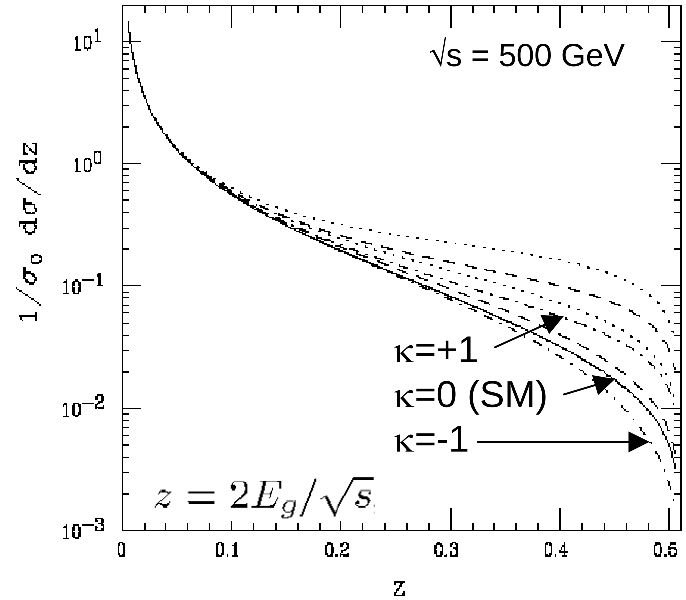
Top Couplings to Gauge Bosons: g

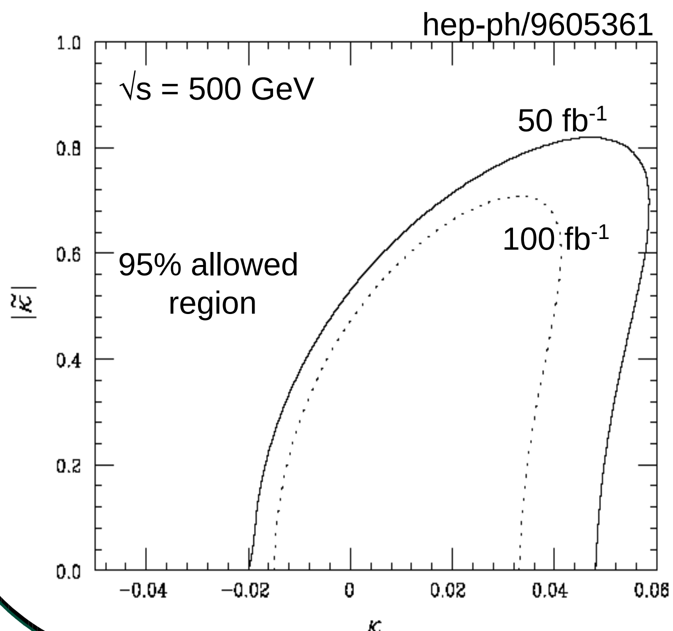
- The g-t-t vertex can be affected by strong dipole moments related to New Physics

$$\mathcal{L} = g_s \bar{t} T_a \left(\gamma_\mu + \frac{i}{2m_t} \sigma_{\mu\nu} (\kappa - i\tilde{\kappa}\gamma_5) q^\nu \right) t G_a^\mu$$

CP-conserving CP-violating

- The Tevatron/LHC will be sensitive to values ~0.1.
- One of the observables in e^+e^- collisions is the energy spectrum of the gluon radiated off the top quark.



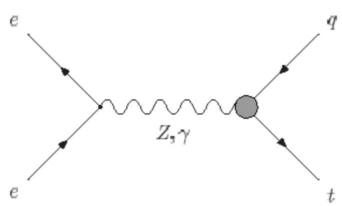


- Reach in chromo-electric dipole moment ($\tilde{\kappa}$) improves by ~x2 for same integrated luminosity at $\sqrt{s}$ = 1 TeV.
- Could make use of additional observables: e.g. spin correlations.

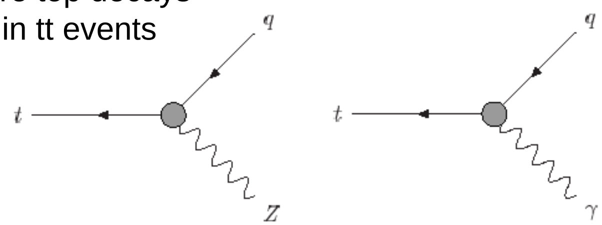
Top Couplings to Gauge Bosons: FCNC

e^+e^- collider:

Single top production



Rare top decays in tt events



hep-ph/0409351
hep-ph/0409342

$\sqrt{s} = 500$ GeV	SM	2HDM-III	MSSM	TC2
$\sigma(\gamma\gamma \to t\bar{c})$[fb]	$\mathcal{O}(10^{-8})$	$\mathcal{O}(10^{-1})$	$\mathcal{O}(10^{-1})$	$\mathcal{O}(10)$
$\sigma(e\gamma \to et\bar{c})$[fb]	$\mathcal{O}(10^{-9})$	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$	$\mathcal{O}(1)$
$\sigma(e^+e^- \to t\bar{c})$[fb]	$\mathcal{O}(10^{-10})$	$\mathcal{O}(10^{-3})$	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-1})$
$Br(t \to cg)$	$\mathcal{O}(10^{-11})$	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-4})$
$Br(t \to cZ)$	$\mathcal{O}(10^{-13})$	$\mathcal{O}(10^{-6})$	$\mathcal{O}(10^{-7})$	$\mathcal{O}(10^{-4})$
$Br(t \to c\gamma)$	$\mathcal{O}(10^{-13})$	$\mathcal{O}(10^{-7})$	$\mathcal{O}(10^{-7})$	$\mathcal{O}(10^{-6})$
$Br(t \to cH)$	$< 10^{-13}$	$\mathcal{O}(10^{-3})$	$\mathcal{O}(10^{-4})$	$\mathcal{O}(10^{-1})$

Hopelessly detectable at the LHC or ILC in any of their scheduled upgrades.

Observation is a clear indication of New Physics!

- Sensitivity is better from production than from decay since, despite the lower S/B, the cross section is larger (q^μ-enhancement for $\sigma^{\mu\nu}$ coupling, larger phase space).
- Beam polarization very useful to improve limits from single top production via a decrease in background (dominated by WW).

3σ discovery limits

hep-ph/0102197

	LHC	ILC	ILC+
$\mathrm{Br}(t \to Zc)\ (\gamma_\mu)$	3.6×10^{-5}	1.9×10^{-4}	1.9×10^{-4}
$\mathrm{Br}(t \to Zc)\ (\sigma_{\mu\nu})$	3.6×10^{-5}	1.8×10^{-5}	7.2×10^{-6}
$\mathrm{Br}(t \to \gamma c)$	1.2×10^{-5}	1.0×10^{-5}	3.8×10^{-6}

Corresponding to one year of running time:
LHC : 100 fb^{-1}
ILC : 300 fb^{-1}, $\sqrt{s}$=500 GeV, no beam pol
ILC+: “ ,$P(e^-)=+0.8$, $P(e^+)=-0.6$

LHC and ILC complementary

Top Coupling to Scalars: Higgs

- The top-Higgs Yukawa coupling is the largest coupling of the Higgs boson to fermions ($g_{ttH} \sim 0.7$ vs $g_{bbH} \sim 0.02$). Precise measurement important since the top quark is the only "natural" fermion from the EWSB standpoint.

<u>Direct measurement</u>

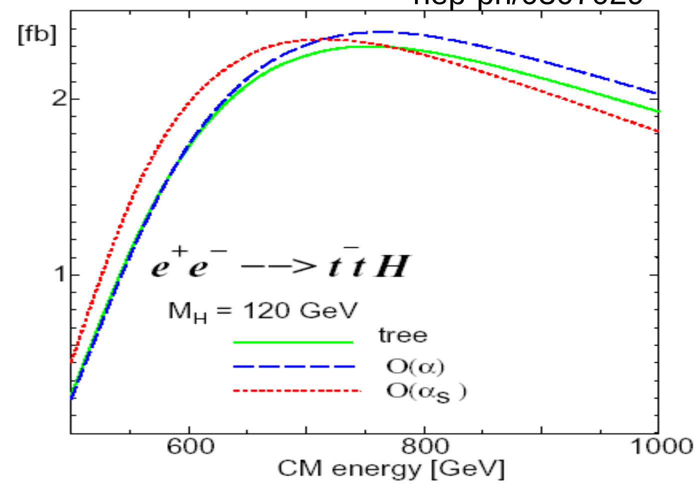
$m_H < 2m_t$: via $\sigma(e^+e^- \to ttH)$

- Spectacular signature: $4b+4q$, $4b+2q+l+\nu$.
- Use of b-tagging and sophisticated multivariate selections crucial.

A. Juste and G. Merino (hep-ph/9910301)
A. Gay et al (4th ECFA/DESY Workshop)

$\sqrt{s}$ = 800 GeV, L = 1000 fb^{-1}
$\Delta g_{ttH} \sim 6(10)\%$ for m_H=120(190) GeV

hep-ph/0307029



$m_H > 2m_t$: via BR($H \to tt$) in $e^+e^- \to H\nu\nu \to tt\nu\nu$

- Signature: 4q+2b+missing energy.
- Visible mass distribution to discriminate against dominant backgrounds: $e^+e^- \to tt$, $e^+e^- \to e^+e^-tt$.

hep-ph/0012109

$\sqrt{s}$ = 1 TeV, L = 1000 fb^{-1}
$\Delta g_{ttH} \sim 2(10)\%$ for m_H=400(600) GeV

<u>Indirect measurement</u> (from tt threshold scan)

- Yukawa potential: $V_{tth} = -\frac{g_{tth}^2}{4\pi}\frac{e^{-m_h r}}{r}$
- Sensitivity almost exclusively from σ_{tt}.
- Multiparameter fit to threshold observables and assuming $\Delta\sigma_{tt}$(theory)~1%(!):

hep-ph/0207315

9+1 scan points, 30 fb^{-1}/point
Multiparameter fit: m_t, Γ_t, g_{ttH}; $\Delta\alpha_s$=0.001 (constraint)
$\Delta g_{ttH} \sim$ +35 -65% for m_H=120 GeV
Large correlation with m_t (+80%)

QCD Physics at the ILC

- The ILC offers the possibility of studying QCD at high energy scales in the experimentally clean, theoretically tractable environment of e^+e^- collisions.
- In addition, virtual $\gamma\gamma$ collisions will be available for free and a $\gamma\gamma$ collider is considered as an option, thus allowing detailed measurements of the relatively poorly understood structure of the photon.

Benchmark main topics:

Will only discuss this

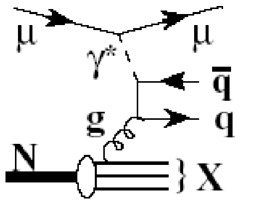
- Precise determination of α_s and its Q^2 dependence
- Measurement of the total $\gamma\gamma$ cross section and the photon structure function

Why?

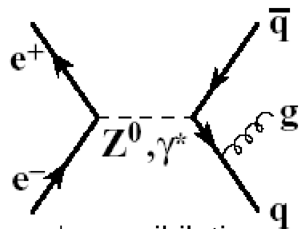
- α_s is the single free parameter of the SU(3) gauge theory of the strong interaction
  $\Rightarrow$ should be measured to highest available precision
- very important to directly measure the Q^2 dependence of α_s over an energy range as wide as possible
  $\Rightarrow$ test QCD or reveal new physics
- renormalization group extrapolations of the U(1), SU(2) and SU(3) coupling strengths constrain physics scenarios at the GUT scale
  $\Rightarrow$ currently limited by few % relative precision in $\alpha_s(m_Z)$

Status of Current α_s Measurements

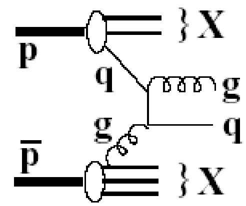
- α_s being determined in a variety of particle reactions involving in- or outgoing quark and gluons. Examples:



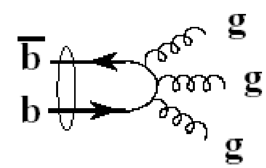
lepton-nucleon scattering (DIS)



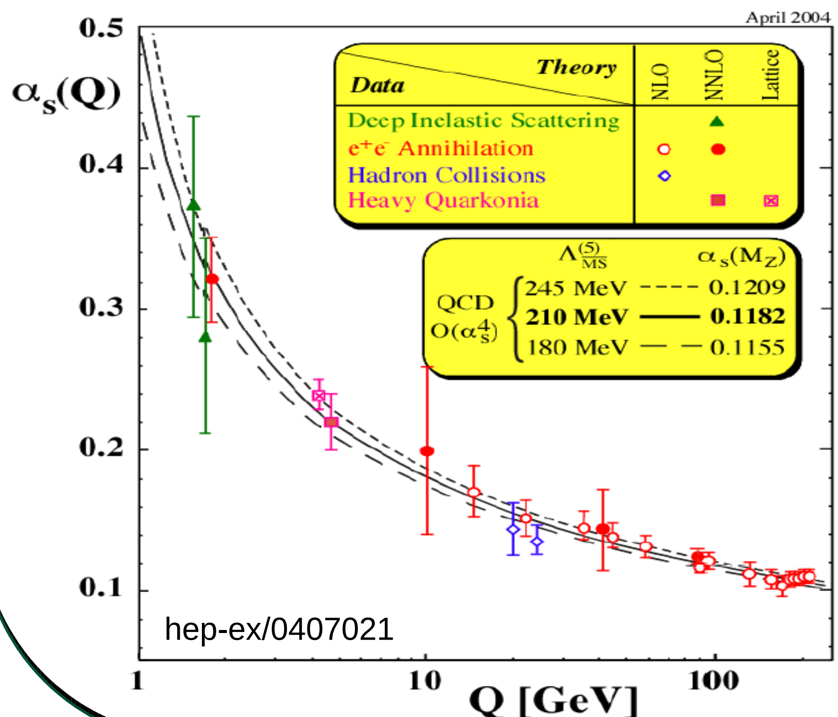
e^+e^- annihilation



hadron-hadron collisions



quarkonia decays



- Accurate theoretical predictions required to relate experimental observables to α_s.
- Measurements at different Q evolved via RGE to Q = m_Z
- World average of $\alpha_s(m_Z)$ obtained from those measurements based on NNLO calculations and having a total uncertainty < 0.008:

hep-ex/0407021

$$
\begin{aligned}
\text{DIS [Bj} - \text{SR]}: &\quad \alpha_s(M_{Z^0}) = 0.121^{+0.005}_{-0.009} \\
\tau\ \text{decays}: &\quad \alpha_s(M_{Z^0}) = 0.1180 \pm 0.0030 \\
\text{DIS } [\nu, \mathrm{xF_3}]: &\quad \alpha_s(M_{Z^0}) = 0.119^{+0.007}_{-0.006} \\
\text{DIS } [\mathrm{e}/\mu, \mathrm{xF_2}]: &\quad \alpha_s(M_{Z^0}) = 0.1166 \pm 0.0022 \\
\Upsilon\ \text{decays}: &\quad \alpha_s(M_{Z^0}) = 0.118 \pm 0.006 \\
\Gamma(\mathrm{Z} \to \text{had}): &\quad \alpha_s(M_{Z^0}) = 0.1226^{+0.0058}_{-0.0038}
\end{aligned}
$$

$$\boxed{\overline{\alpha_s}(M_{Z^0}) = 0.1182 \pm 0.0027}$$

Measurements of α_s at the ILC

Event shape observables

- Sensitive to the 3-jet nature of the particle flow: e.g. thrust, jet masses, jet rates, etc
- Procedure: form a differential distribution, correct for detector/hadronization effects and fit a pQCD prediction to the data, allowing $\alpha_s(m_Z)$ to vary
- Expected uncertainties:

	Current(LEP/SLC)	ILC(500 GeV)
Statistical	<0.001	<0.0005
Systematics		
Detector	0.001-0.004	$\leq$0.001
Backgrounds	negligible	<0.001
Hadronization corrections	$\geq$0.001	<0.001
Theoretical (NLO(+resum))	~0.006	~0.005

~few x 10^5 $e^+e^-\to qq$ events/year

Hermetic detector, good tracking efficiency+resolution, good calorimeter energy resolution.

Sizeable WW,ZZ and tt bckg. Kept under control using e^-_R beam and b-tagging veto.

Scales at least as fast as ~$1/\sqrt{s}$

- A 1% measurement is experimentally feasible but…need event shape observables at NNLO!!

The tt(g) system

- tt at threshold: already discussed. Recall:

  Simultaneous determination of m_t, α_s and Γ_t from fit to threshold observables.
  Assume 3% theoretical error on σ_{tt} and 9+1 point scan with 30 fb^{-1}/point:
  $\Delta m_t(1S)$=19 MeV, $\Delta\alpha_s$=0.0012, $\Delta\Gamma_t$=32 MeV ,ρ_{ij}<0.5
  $\Rightarrow$ very important to control absolute normalization of the cross section.
  Need to take into account previously neglected %-level effects.

Measurements of α_s at the ILC (cont'd)

Ratio Method

- Make use of the inclusive ratios $\Gamma_z^{had}/\Gamma_z^{lept}$, $\Gamma_\tau^{had}/\Gamma_\tau^{lept}$, which depend on α_s via radiative corrections. Current state of the art is NNLO.
- Pros: inclusive observables suffer from small experimental systematics
  (e.g. $\Delta\alpha_s$(exp syst)~0.001@ LEP/CLEO)
  Cons: require large statistics
  (e.g. $\Delta\alpha_s$(stat)~0.0025 @ LEP from 16M Z events using $\Gamma_z^{had}/\Gamma_z^{lept}$)

- GigaZ: ~10^9 Z events
  $\Gamma_z^{had}/\Gamma_z^{lept}$: $\Delta\alpha_s$(stat)~0.0004, $\Delta\alpha_s$(exp syst)~0.0008
  Current estimates of theoretical uncertainties:
  - Conservative: last calculated term ($O(\alpha_s^3)$) ; $\Delta\alpha_s$(theo)~0.002
  - "Standard" (optimistic): estimated $O(\alpha_s^4)$ term; $\Delta\alpha_s$(theo)~0.0006
  - Scale variation: $m_Z/3 - 3\ m_Z$; $\Delta\alpha_s$(theo)~+0.002 –0.00016

  $\Gamma_\tau^{had}/\Gamma_\tau^{lept}$: $\Delta\alpha_s$(stat+exp syst)~0.001 already at LEP/CLEO!!!!
  Considerable debate about theoretical uncertainties: $\Delta\alpha_s$(theo)~0.001$\leftrightarrow$0.005
  If the theoretical uncertainties improved/clarified, this could offer a further 1%-level measurement.

- Ongoing NNNLO QCD calculations. Expected to be available within next few years.

Q^2 Evolution of α_s

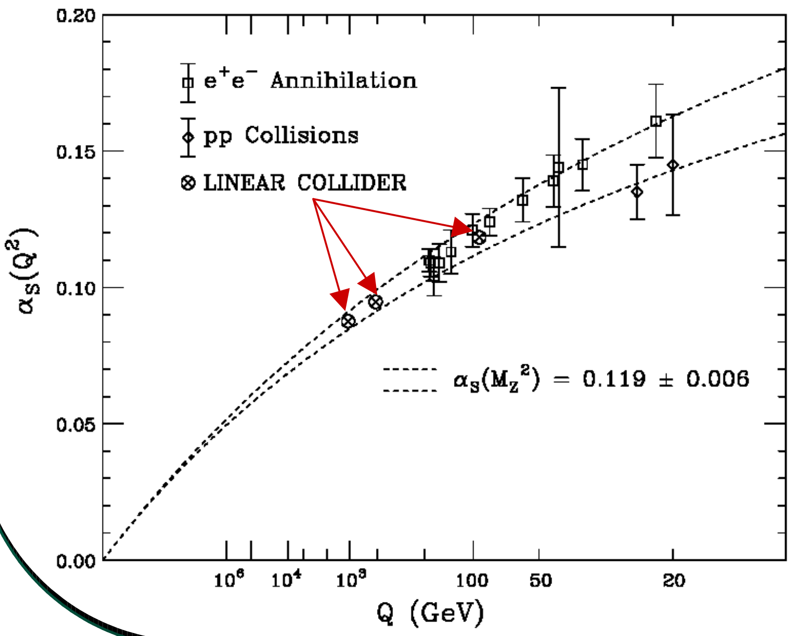
- Translation of measurements of $\alpha_s(Q)$ ($Q \neq m_Z$) to $\alpha_s(m_Z)$ requires the assumption that the "running" of α_s is given by the QCD β-function.

  $\Rightarrow$ very important to measure such running directly since it reflects the non-Abelian dynamics

  $\Rightarrow$ deviations from the expected running may appear at scales above the threshold for pair-production of new colored particles.

- For this measurement, the Q-dependence of α_s, rather than its absolute value, is what's important as many systematic uncertainties cancel.

  $\Rightarrow$ desirable to measure α_s at different values of Q, using the same detector, technique and applying the same treatment to the data.



Example:

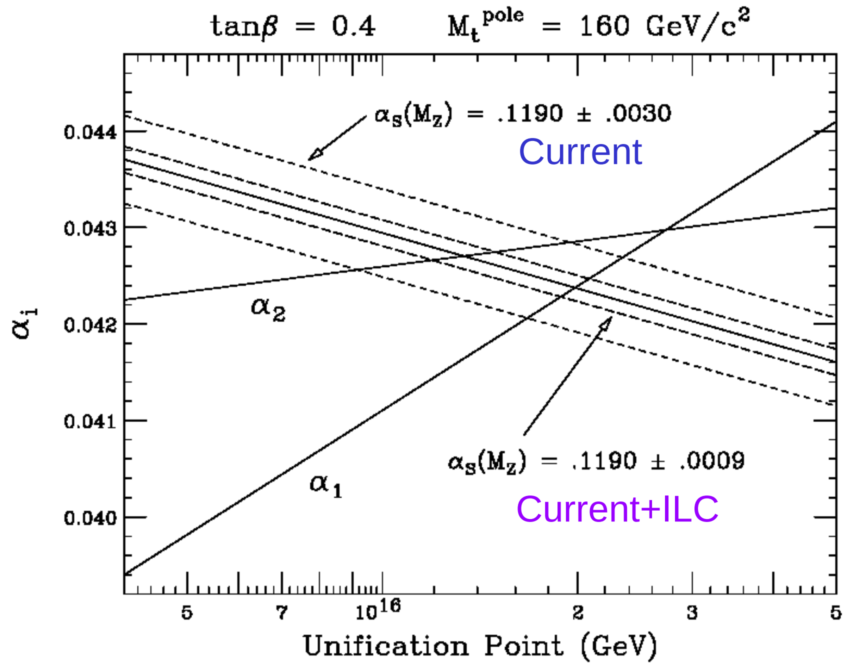
- ILC measurement at $\sqrt{s}$=91 GeV ($\Gamma_z^{had}/\Gamma_z^{lept}$ or jet rates)
  $\sqrt{s}$=500,1000 GeV (jet rates)
- Assume 1% theoretical uncertainty for all three $\sqrt{s}$
- Simultaneous determination of $\alpha_s(m_Z)$ and β_0(~0.61 in the SM)

	$\Delta\alpha_s(m_Z)$	$\Delta\beta_0$
Current data only	0.0030	0.042
ILC only	0.0018	0.034
Current data+ILC	0.0009	0.016

Q^2 Evolution of α_s (cont'd)

- Since the weak and electromagnetic couplings are known with much better precision, the current uncertainty on α_s is the dominant uncertainty in the "prediction" of the GUT scale.

- A 1% α_s measurement at the ILC will lead to a significant improvement in the extrapolation of α_s to the GUT scale, and thus contribute to place more stringent constraints on beyond-SM physics scenarios.



Conclusions

- Elucidation of the dynamics responsible for EWSB constitutes the main goal for particle physics research in the next 20 years.
- The LHC will be probing the relevant energy scale and should definitelly discover signs of the EWSB dynamics. The ILC will complement the LHC by providing essential information to interpret and exploit these discoveries.
- In particular, the ILC shows the promise of precision measurements in top and QCD which will, under any circumstances, be crucial to point to the relevant energy scales and to possible extensions of the Standard Model.